PS Preliminary Assessment of the CO_2 Storage Capacity in the Lower Copper Ridge Dolomite (Upper Cambrian), Northeastern Kentucky*

J. Richard Bowersox[1], Stephen F. Greb[1], and David C. Harris[1]

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Abstract

The Kentucky Geological Survey drilled its 1 Hanson Aggregates stratigraphic research well, Carter County, northeast Kentucky, to identify potential CO_2 storage reservoirs in the Knox Group and deeper strata, identify potential confining intervals, and test reservoir rock properties in the southern Appalachian Basin. The lower Copper Ridge Dolomite of the Knox (3313 - 4170 ft) was evaluated to determine porosity and permeability as a standalone CO_2 storage reservoir. The interval is composed almost exclusively of dolomite with occasional thin sandstone and shale interbeds. Average porosity calculated in the entire lower Copper Ridge is 5.8% and permeability measured in core plugs ranges from less than 0.001 mD to 34 mD.

A step-rate test was conducted in the Copper Ridge from 3695–3945 ft, an interval that showed substantial vugular porosity in cores. The interval was isolated at its base by a cast iron bridge plug and cement plug at 3945–3963 ft to prevent pressure communication and fluids loss to underlying strata during testing, effectively abandoning the wellbore below 3963 ft. The interval with swabbed through tubing in 19 runs prior to the step-rate test to recover formation water, recovering 43 barrels of water. Analysis of the water sample showed 114,900 mg/l residue total dissolved solids. A static bottom hole pressure was obtained followed by the step-rate test. The test featured stable pumping rates from 0.25 to 5.5 BPM in 5-minute steps but was terminated when the supply of fresh drinking water test-fluid was exhausted. After completion of the final step the well was shut-in and pressure falloff monitored for about 12 hrs. The lower Copper Ridge test interval fractured at a pressure of 1979 psi, or a fracture gradient of 0.60 psi/ft. Average permeability of the test interval calculated from the falloff pressure was 15.3 mD.

Porosity and net reservoir thickness for calculating potential CO_2 storage volume in the lower Copper Ridge were determined using an industry-standard 7% porosity cutoff. Average reservoir thickness in the study area at the cutoff is 71 ft and porosity is 9.0%. Net lower Copper Ridge reservoir pore volume in the 615,450-acre potential storage area is about 4.0 million acre-feet. CO_2 storage volume was determined using the methodology of the U.S. DOE, Office of Fossil Energy, National Energy Technology Laboratory. Estimated P50 CO_2 lower Copper Ridge storage volume is about 1320 metric tons/acre and 811 million metric tons in the study region. Thus, about 760 surface acres would be required to store 1 million metric tons of CO_2, the average annual CO_2 released by a coal-fired power plant in the Ohio River industrial corridor.

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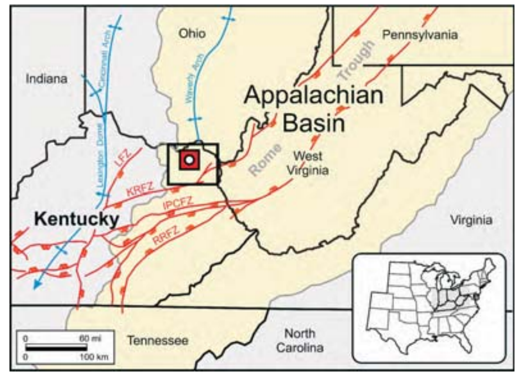
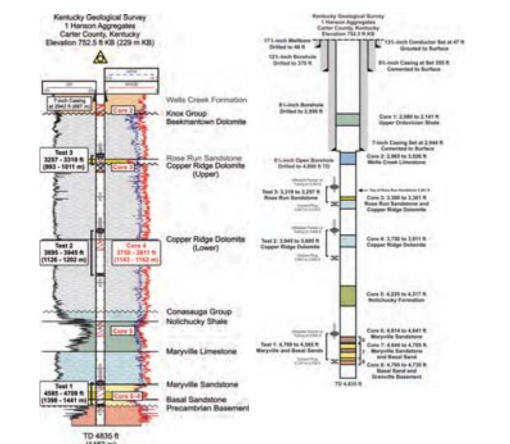


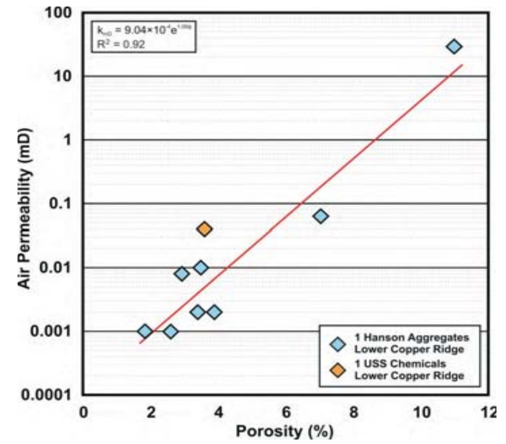
Location of the Kentucky Geological Survey's 1 Hanson Aggregates well in Carter County, northeast Kentucky. The well location was chosen at a location in the East Kentucky Coal Field where a cooperative land owner granted access and where all potential reservoir zones and Precambrian basement could be reached at a drill depth less than 5,000 ft.

KGS 1 Hanson Aggregates Well Design

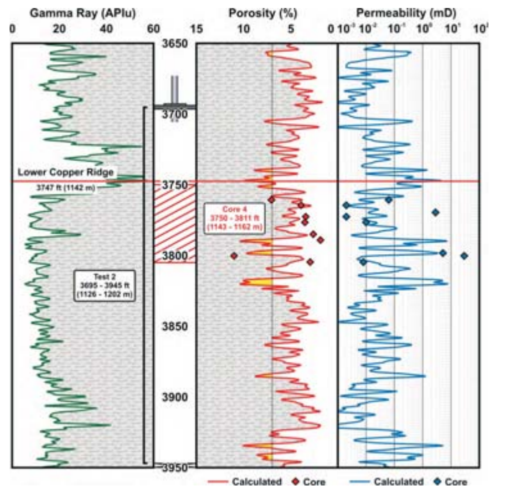


Correlated Formation density log (left) from the top of the Knox Group to the well TD in Precambrian Grenville granite gneiss basement showing core and step-rate test interval depths. Well construction diagram of the 1 Hanson Aggregates (right) showing details of the casing program, cores, and step-rate test intervals.

Lower Copper Ridge Porosity

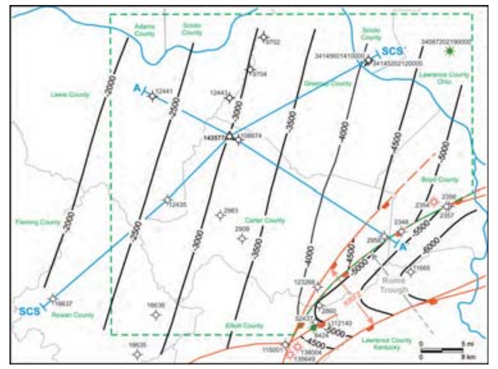


Porosity/permeability crossplot of the nine core plugs from the lower Copper Ridge. The lower Copper Ridge was a backup hazardous waste disposal zone in wells located in south-central Ohio, about 19 mi northeast of the 1 Hanson Aggregates well. Regression shows an excellent porosity/permeability relationship in these core plugs.

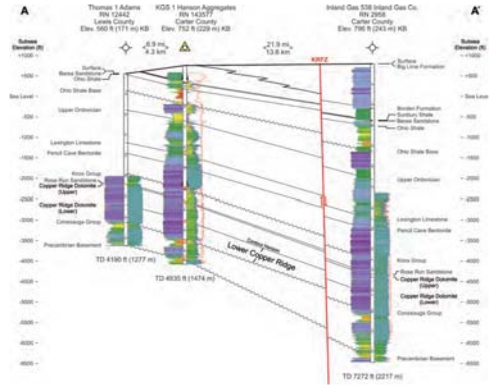


Lower Copper Ridge gamma ray and porosity logs showing calculated porosity and permeability the cored and test intervals. Yellow shaded intervals on the log exceed 7% porosity, the industry-standard cutoff for evaluating CO_2 storage capacity.

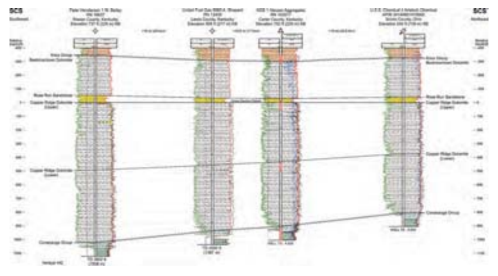
Geology



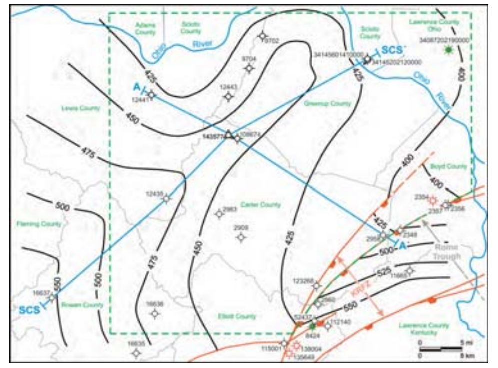
Structural contours on top of the lower Copper Ridge show gentle dip (< 1°) in the region to northwest of the Kentucky River Fault Zone.



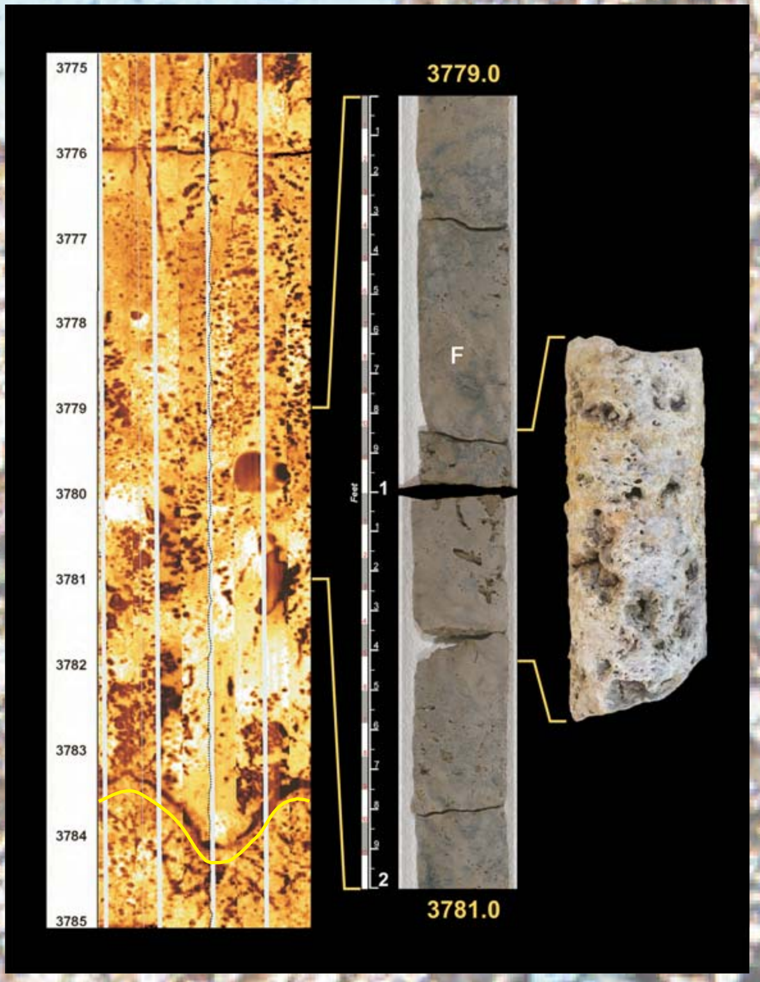
Structural dip cross section through the KGS 1 Hanson Aggregates well. Vertical exaggeration ×28.



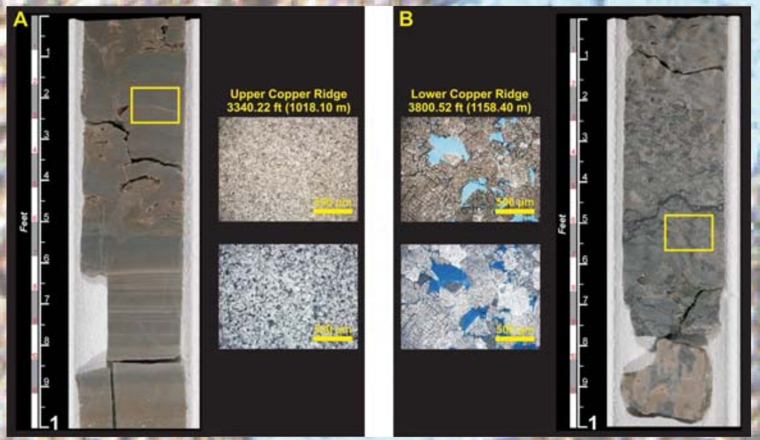
Stratigraphic cross section through the Knox Group shows thinning of lower Copper Ridge to the northeast (mapped below). Vertical exaggeration ×13.



Lower Copper Ridge isopach thickness shows about 125 ft of thinning to the northeast from Rowan County to the Ohio River.



Formation Imaging Log and cores from the lower Copper Ridge test interval. Note the large vugs developed in this zone that provide the bulk of the porosity. The lower Copper Ridge has safely been used for produced water and hazardous waste disposal for decades in Ohio and Kentucky. A natural fracture intersecting the wellbore is highlighted



Thin section photomicrographs from the Copper Ridge showing intercrystallline microporosity in the upper Copper Ridge (left) compared to the larger intercrystalline pores in the lower Copper Ridge (right) that would comprise a CO_2 storage interval.

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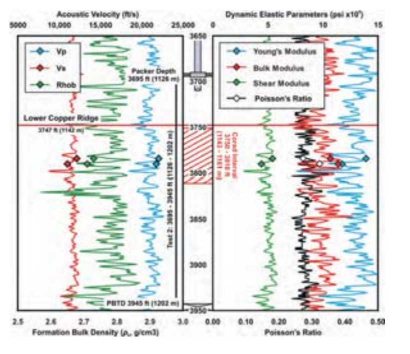
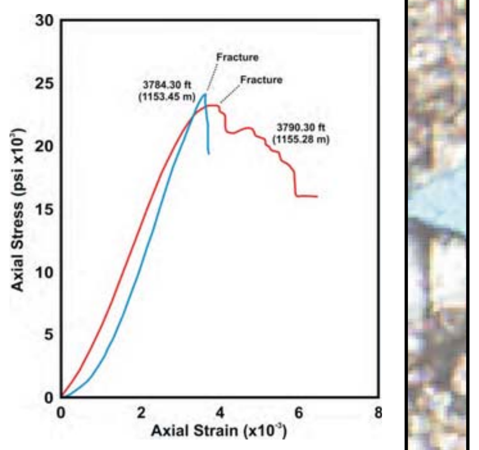
Geomechanical Rock Properties

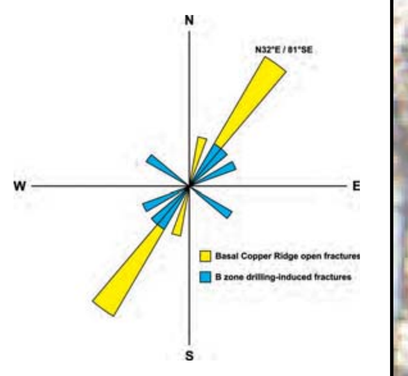


Dynamic elastic geomechanical properties, how the rock is affected by subsurface stress and strain, were measured in core plugs (colored diamonds) and calculated from acoustic and density log data in the 1 Hanson Aggregates well. There are four inter-related rock properties (SPE PetroWiki): Young's modulus is the ratio of uniaxial compressive (tensile) stress to the resultant strain; Bulk Modulus is the change in volume under hydrostatic pressure (i.e., the ratio of stress to strain; Bulk Modulus is the reciprocal of compressibility.); and Shear Modulus is the ratio of shearing (torsional) stress to shearing strain. An additional parameter, Poisson's Ratio, is a measure of the geometric change of shape under uniaxial stress.

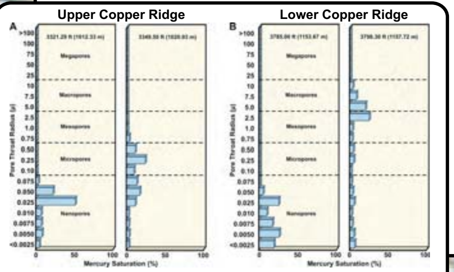
This figure shows the geomechanical properties of the lower Copper Ridge in the step-rate test interval. Colored diamonds are acoustic, bulk density, and geomechanical properties measured in core plugs from corresponding depths. Log and calculated values are generally a good match to the properties measured in the core plugs, although influenced by preferential sampling of the core plugs versus the 0.5-ft (0.15-m) sampling interval of the logs.



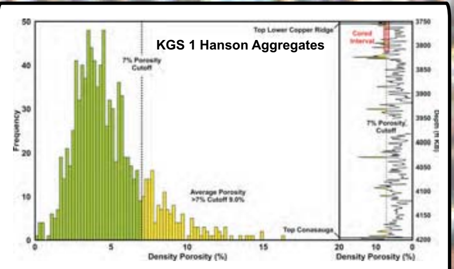
Comparison of rock strengths in axial stress tests of two core plugs from the lower Copper Ridge show similar axial stress and strain before fracturing. This suggests that the lower Copper Ridge would be unlikely to fracture at typical CO_2 injection pressures and thus effectively preserve reservoir integrity.



Plot of orientations natural fractures and drilling-induced fractures interpreted from the FMI and UBI logs in the lower Copper Ridge. Open and drilling-induced fractures and their conjugates parallel the modern tectonic stress axis. Fractures in a formation both enhance porosity and permeability, provide pathways for migration of fluids outside of the storage reservoir. A natural fracture intersecting the wellbore is highlighted on the FMI log (left).

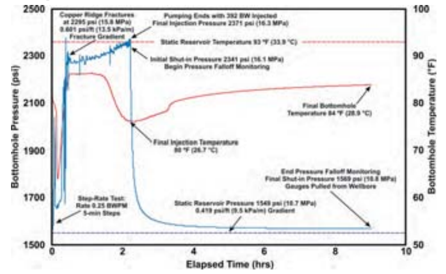


Pore throat radius histogram from MICP analysis of a core plugs from a potential confining layers in the upper Copper Ridge (left) and confining and reservoir intervals in the lower Copper Ridge (right). Confining intervals have pore throat radii well within the nanopore range, whereas the reservoir interval in the lower Copper Ridge has pores in the meso- to macropore range.

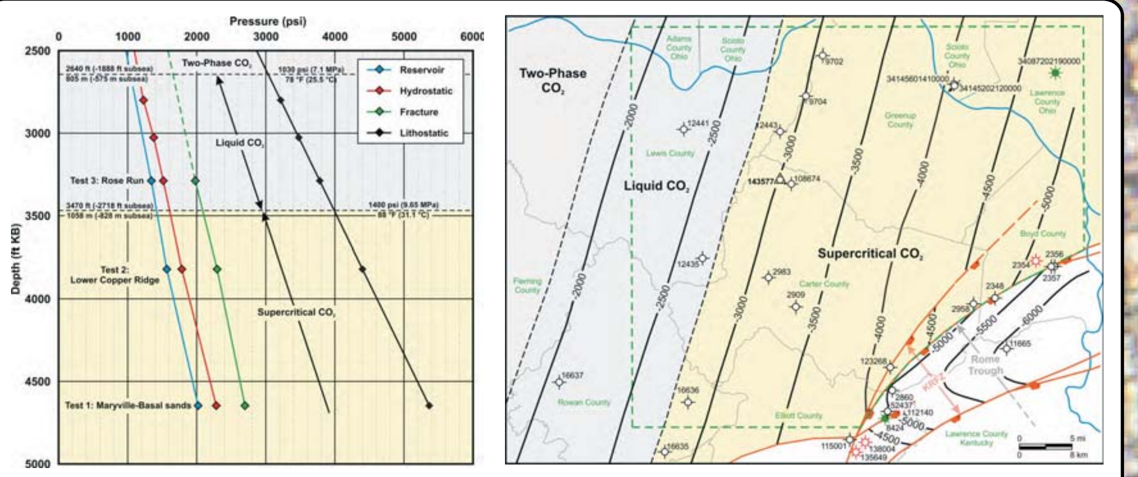


Histogram of lower Copper Ridge porosity annotated to show the cutoff porosity versus total porosity. The average porosity of all wells in the study area was 5.8%, and net porosity greater than the 7% porosity cutoff is 9.1%.

Step-rate Test



Annotated plot of pressure from the step-rate test of the lower Copper Ridge in interval 3,695 - 3,945 ft PBTD. Injection rate proceeded in 0.25 BWPM steps every 5 minutes. The test interval appears to have fractured at 2,295 psi, yielding a fracture gradient of 0.601 psi/ft after 9.5 BW had been injected. Secondary fractures began to develop after pumping 36 BW and pressure had built to 2,301 psi. Pressure subsequently slowly increased to a maximum of 2,371 psi after injecting 392 BW, at which time the test concluded and the wellbore shut-in because of mechanical problems with the injection pump. Pressure falloff was monitored for 6.8 hrs, after which pressure gauges were removed from the well and the test interval was permanently abandoned with cement plugs.



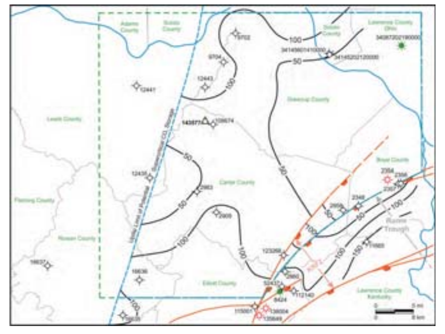
Subsurface pressure plots (left) from the 1 Hanson Aggregates well annotated with corresponding CO_2 pressure-temperature phases from Freund and others (2005). Static reservoir pressures and fracture pressures were measured during step-rate tests of wells in region. Hydrostatic pressure was calculated from the density of formation brines sampled in the region. Lithostatic pressure was calculated from density log data. The critical point of CO_2 is at 1,071 psi and 88.0 F. The Copper Ridge reservoir is underpressured, and reaches 1,071 psi reservoir pressure at about 2,720 ft (-2,718 ft subsea elevation), 445 ft deeper than would be expected from its formation water density. The low geothermal gradient in the 1 Hanson Aggregates, however, caused the reservoir temperature to reach the critical temperature of 88.0 F at a drill depth of 3,470 ft, a structural subsea elevation of -2,718 ft, thus reducing the area available for supercritical CO_2 storage (right).

CO_2 Storage Capacity at Reservoir Porosity > 7%

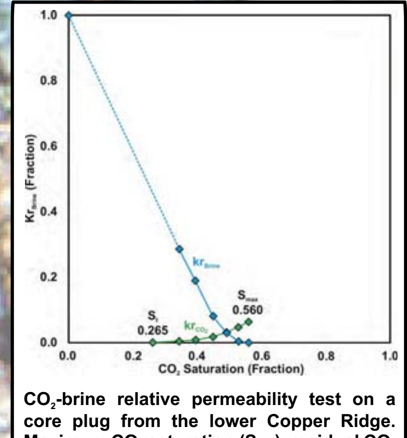
ϕ > 7% (avg %)	h_n > 7% (net ft)	V_{pr} > 7% (ac-ft/ac)	ρ_{CO_2}* (kg/m³)	(t/ac-ft)	Dolomite E_{saline} P10	P50	P90	G_{CO_2} (t/ac) P10	P50	P90	Evaluation Area G_{CO_2} (Mt)** P10	P50	P90
9.1	71	6.5	784	967	0.160	0.210	0.260	1004	1318	1631	618	811	1004

*ρ_{CO_2} 0.784 t/m3 at reservoir conditions; Peace Software, www.peacesoftware.de/einigewerte/co2_e.html
**615,450-acre (249,000-hectare) evaluation area

The 1 Hanson Aggregates penetrated an net total of 71 ft of potential storage reservoir in the lower Copper Ridge with porosity > 7%, averaging 9.1% in the evaluation area. P_{50} reservoir volume, however, is insufficient to store the average annual CO_2 emissions from a source in the Ohio River industrial corridor.



Preliminary isopach map of net lower Copper Ridge >7% porosity cutoff. The evaluation area isoutlined by the blue dashed line. Total reservoir volume in the evaluation area is 4 million acre-feet, and net pore volume available for CO2 storage (rock volume × porosity) is 364,000 acre-feet.



CO_2-brine relative permeability test on a core plug from the lower Copper Ridge. Maximum CO_2 saturation (S_{max}), residual CO_2 saturation (S_t), and relative permeability to brine (kr_{Brine}) and CO_2 (kr_{CO_2}) are posted. S_t in both plots was determined by regression. Capillary trapping efficiency, the percentage of residually-trapped CO_2 ($R_{\%} = (S_t/S_{max})\times100$; Burnside and Naylor, 2014), is 29.5%. That is, ~30% of CO_2 injected into the lower Copper Ridge would be trapped in the pore space and unable to migrate out of the reservoir in the event of a seal failure.

Acknowledgements

This research was funded by the Commonwealth of Kentucky through the Energy Independence and Incentives Act of 2007. Access to the drill site was granted by Hanson Aggregates, Grayson, Kentucky, without which this project would not have been possible. MICP testing was provided by the Indiana Geological Survey, Bloomington, Indiana, and rock strength testing was provided by the Battelle Memorial Institute, Columbus, Ohio. All core analysis was performed by Core Laboratories, Houston, Texas, except rock strength testing which was performed by Weatherford Laboratories, Houston, Texas. Wellsite drilling and testing was supervised by Geostock Sandia Technologies, Houston, Texas.

KGS geologists Marty Parris (left) and Steve Webb (right) preparing to collect a formation water sample from the lower Copper Ridge step-rate test interval prior to the test.

Kentucky Geological Survey